AUTOMATED GUIDED VEHICLES AT THE NATIONAL BUREAU OF STANDARDS AUTOMATIC MANUFACTURING RESEARCH FACILITY

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Commercial equipment is identified in this paper in order to adequately describe the systems that were developed. In no case does such identification imply recommendation by the National Bureau of Standards, nor does it imply that this equipment was necessarily the best available for the purpose.

The National Bureau of Standards is currently building the Automated Manufacturing Research Facility (AMRF), as a testbed for the factory of the future.[1] When complete, the facility will consist of three machining workstations, a cleaning and deburring workstation, an inspection workstation and a materials handling workstation. Each workstation consists of a number of devices (a robot, a machine tool, fixtures, etc.) which are fully automated. A single controller, i.e., a workstation controller, commands and coordinates the operations of these devices. Each workstation is designed to operate either in a stand-alone mode or in an integrated fashion with other workstations under the supervision of a higher level controller.

Materials transfer is coordinated by the

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Material Handling Workstation Controller (MHWC) which is responsible for materials flow throughout the facility. As currently implemented, the MHWC monitors material inventory and directs the activities of an Automatic Guided Vehicle (AGV) which is used to transport materials to and from each workstation. An AGV was selected for material transport rather than some type of conveyor or overhead system because of the special requirements of the AMRF. Since this is a research facility, it is important that the material transport system be flexible, easily reconfigured and capable of handling a variety of material types, shapes, sizes and weights. The AGV system that was selected meets all of these requirements and is relatively small in size and highly maneuverable. This paper briefly describes the control concepts used in the AMRF and how a particular AGV was modified and integrated into this facility.

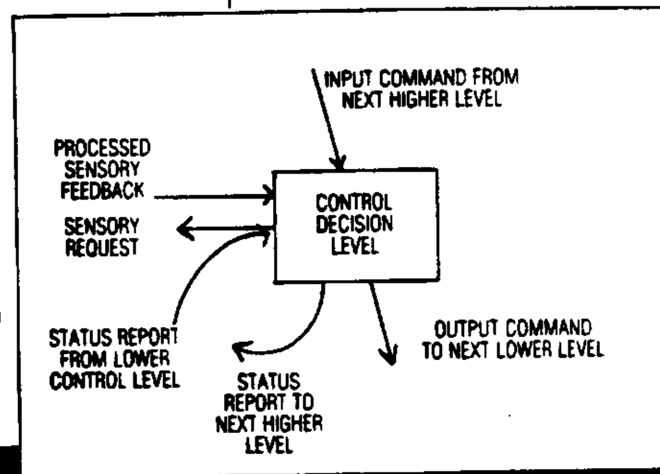

FIGURE 1. GENERIC CONTROL LEVEL.

AMRF Hierarchical Control Structure

The control architecture of the AMRF is based on a sensory-interactive modular hierarchical feedback system.[2,3,4,5,6] Each controller, both at the workstation and at higher levels, consists of a collection of control modules which are arranged in a hierarchical multi-level system and which interact through a communications network. Each control module takes commands from only one higher level module in the system, but it may direct several other modules at the next lower level (see *Figure 1*). Tasks enter the system at the highest level and are decomposed into sequences of subtasks to be executed as procedures at that level, or output as commands to the next lower level. Any number of these generic control levels can be combined to form a complex control system (see *Figure 2*).

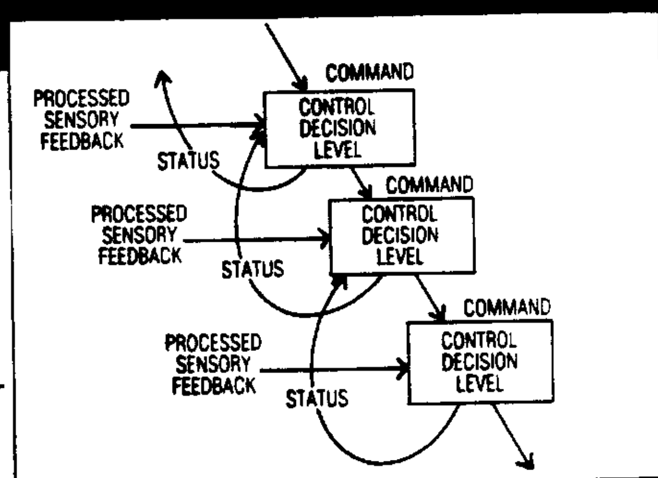

FIGURE 2. HIERARCHICAL CONTROL LEVELS LINKED TOGETHER TO FORM A COMPLEX CONTROL SYSTEM.

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The general control architecture currently implemented in the AMRF is shown in *Figure 3*. At the top of the hierarchy is the Cell Controller which accepts orders for machined parts and distributes the required work between the workstations under its control. A command and feedback protocol exists between levels of the hierarchy to effectively execute given commands. Typically, commands flow down and status information feeds up the hierarchy. Any device that is integrated into the AMRF needs to conform to this protocol.

The Material Handling Workstation Controller residing under the cell can have at its disposal a variety of devices used for transporting work pieces and tooling to and from the workstations and inventory. An AGV, also called the Cart, operates on the shop floor under control of the MHWC, in the following manner. The parts required for a finished product are ordered up from inventory. A tray tender loads a tray according to instructions which are sent from the MHWC and displayed on a computer terminal. Once loaded, the tray is placed on the Cart and is ready for delivery. A wire on the shop floor routes the Cart past all the workstations. Each workstation has at least one tray transfer station which interacts with the Cart to pass trays back and forth. After the tray tender acknowledges the Cart has been loaded, MHWC can give commands to the Cart to drop the tray off at any tray station. Also since a part may require several machining processes, the Cart can pick-up and transfer the parts between appropriate workstations. Actual locations on the shop floor

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are marked with magnet codes, readable by the Cart, which indicate tray stations, track branches, and stopping points. Optical sensors are used for fine alignment between Cart and tray stations, as well as for location of trays and obstacle detection.

Modification of the AGV

The original Cart, a Model 5366 Prontow Electroguide Driverless Tractor made by Control Engineering Company, had no means for external control, remote communications or dynamic programming necessary for integration into the AMRF. A matrix diode board was used to connect a front panel switch with a particular function (stop, go to-station etc.), and also a magnet code location where the function was to take place (see *Figure 4*). After the board was programmed by plugging diodes into appropriate locations, the functions were activated by throwing one or more of the panel switches. Once underway, the Cart could not be reprogrammed until it returned to the tray tender station. In order to dynamically change the operations that the Cart was to perform, a remote means of reprogramming the diode board and throwing the switches was needed.

The integration of the Cart into the hierarchical control structure is illustrated in *Figure 5*. A telephone line and modem with multiplexer provides communication between the MHWC (running on a remote VAX II/780) and the shop floor. A serial link connects to a switch box which can route signals from the MHWC or operator terminal to a base station Radio Frequency (RF) modem. This modem then communicates to the mobile RF modem which was installed on-board the Cart. To provide the necessary programming and control capabilities the diode matrix board was removed and replaced by an on-board microcomputer system. This system consists of a Multibus four-slot bucket, isolated power supplies, an INTEL 86/12 single board computer and a strip of optically isolated modules to interface this system to the existing Cart electronics.

Description of the MHWC/VAX to Cart Interface

The MHWC communicates to the integrated factory on the shop floor through
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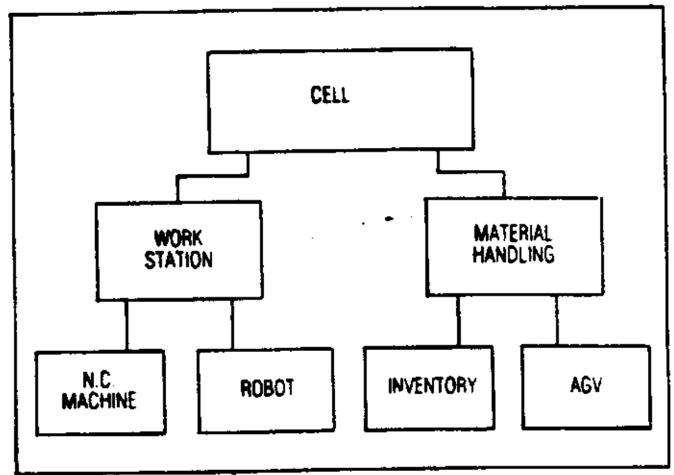

FIGURE 3. HIERARCHICAL STRUCTURE OF THE AMRF.

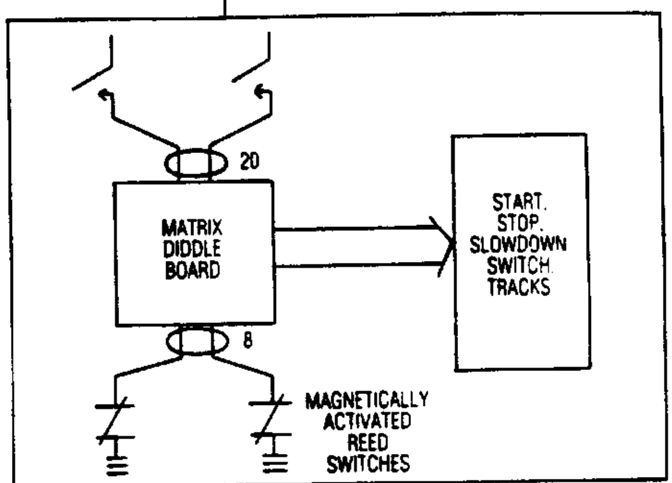

FIGURE 4. ORIGINAL PROGRAM FEATURES OF CART.

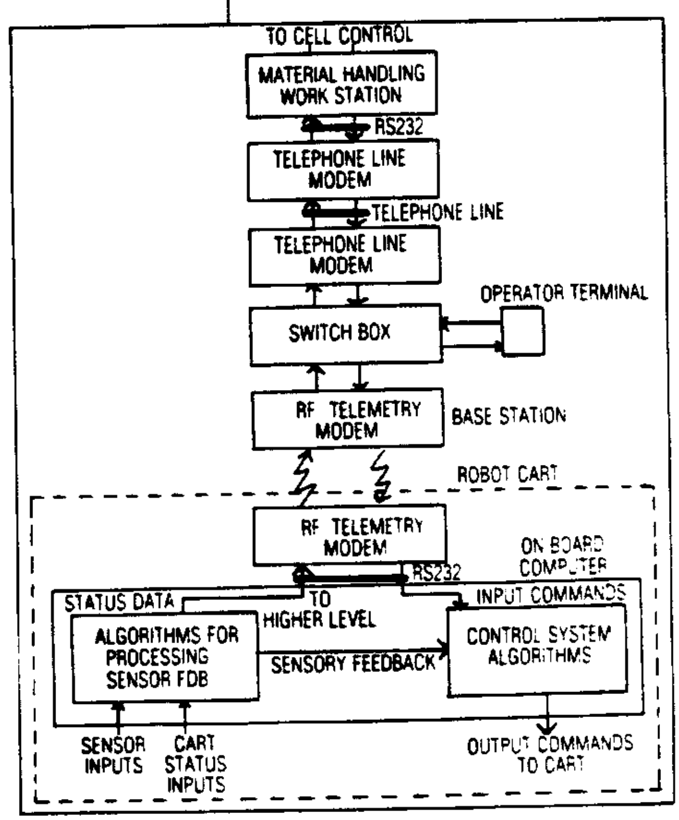

FIGURE 5. HIERARCHICAL CONTROL IMPLEMENTATION OF ROBOT CART.

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an eight channel telephone line modem system. A multiplexer system combines and separates the communication channels at both ends of the telephone line. Two RS232 serial lines are used by the MHWC: one for the tray tender terminal, the other for communicating directly with the Cart. The Cart link is routed through a switch box that can switch Cart control between the MHWC or a terminal used for manual operation. If desired, an RS232 Communications monitor can be used to keep track of the MHWC to Cart transmissions.

From the switch box, the RS232 interface cable connects to an RS232 port on a base station Radio Frequency (RF) Telemetry Modem. The RF Telemetry Modem provides the necessary frequency modulation, demodulation and supervisory control functions to provide for a full duplex data link to the Cart. The modulator/demodulator utilizes frequency shift keying (FSK) for up to a 1200 baud rate of communication. The base telemetry modem transmits at 415.85 Mhz and receives at 409.95 Mhz. Special government-assigned frequency bands are required in order to meet Federal regulations concerning RF communications. The modem on the Cart can be configured to transmit and receive simultaneously. The transmitter on the Cart can be set to be on continuously or can be keyed (powered up) only during transmit cycles. The latter mode requires RTS-CTS handshaking. The RS232 port on the remote RF modem is connected serially to the on-board 86/12 computer to complete the VAX to Cart interface.

Description of the On-board Computer to Cart Interface

An Intel 86/12 single board computer (see *Figure 6*), which resides in a four-slot Multibus bucket mounted inside the Cart, not only replaces the diode matrix board and panel switches but also runs control algorithms and performs sensor data processing and Cart status monitoring. The extra three slots allow for possible future expansion requirements such as a communications network board, analog-to-digital or digital-to-analog boards, or additional parallel input/output (I/O) ports. The 86/12 provides three 8 bit parallel I/O ports which are TTL logic level compatible. The ports on the computer are con-

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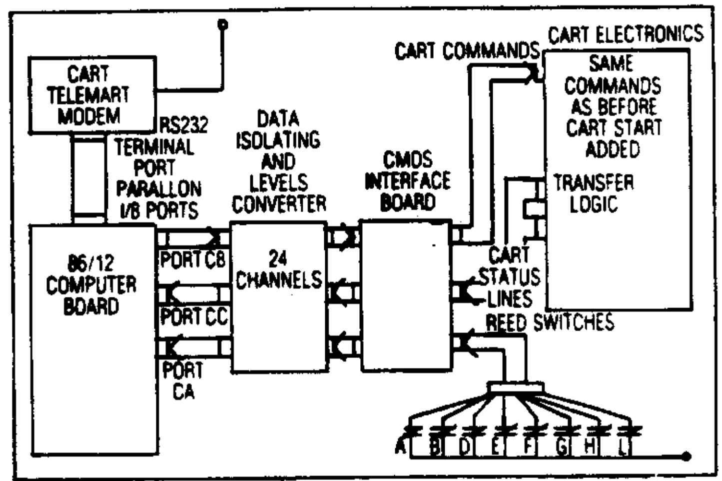

FIGURE 6.

TABLE 1.

DESCRIPTION	PORT IN HEX	BIT NO.	CONFIGURED AS DRIVER OR INPUT
Magnet reed switch 8	CA	7	INPUT
Magnet reed switch 7	CA	6	INPUT
Magnet reed switch 6	CA	5	INPUT
Magnet reed switch 5	CA	4	INPUT
Magnet reed switch 4	CA	3	INPUT
Magnet reed switch 3	CA	2	INPUT
Magnet reed switch 2	CA	1	INPUT
Magnet reed switch 1	CA	0	INPUT
OK TO TRANSFER	CC	3	INPUT
OK TO RELEASE	CC	2	INPUT
SPACE AVAILABLE	CC	1	INPUT
LS-2	CC	0	INPUT
OPTIC BLOCK	CC	4	INPUT
GUIDE SAFE	CC	5	INPUT
BRAKE SET	CC	6	INPUT
TRAVEL DRIVER	CC	7	INPUT
START	C8	7	DRIVER
	C8	6	DRIVER
TRANSFER	C8	5	DRIVER
	C8	4	DRIVER
SLOWDOWN	C8	3	DRIVER
SWITCH TO 615K	C8	2	DRIVER
SWITCH TO 10K	C8	1	DRIVER
STOP	C8	0	DRIVER

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figured for the I/O signals as listed in Table 1. Port CA (hex address) monitors status of magnetic reed switches on the Cart. Magnets mounted in the factory floor can be arranged to provide coded information as to the location of the Cart when it crosses the floor magnet. Port CC is used for monitoring the status of the Cart logic electronics during tray transfers at loading and unloading stations and also for monitoring the status of the Cart drive, guidance, safety and brake activation systems. Port CA is configured as a driver port for command signals to the Cart electronics, which include Cart START, TRANSFER tray, Cart SLOWDOWN, Cart SWITCH to 6.5Khz guidance signal, Cart SWITCH to 10Khz and Cart STOP.

Multibus power requirements (+12, -12, +5 vdc.) are met using isolated output switching power supplies, which provide dual voltage polarities from a single DC voltage source and provide good regulation at higher efficiencies. It should be noted that the Cart does not use chassis as ground, thereby reducing the effects of a shorted wire. Possible interface problems on the computer board from Cart switching transients had been anticipated and the computer power supplies and all I/O interface channels were isolated from the Cart's power and signal lines. In addition to isolation, the interfaces provide buffering from Cart electronics and convert 5 volt TTL levels to 12 volt CMOS levels.

[redacted]

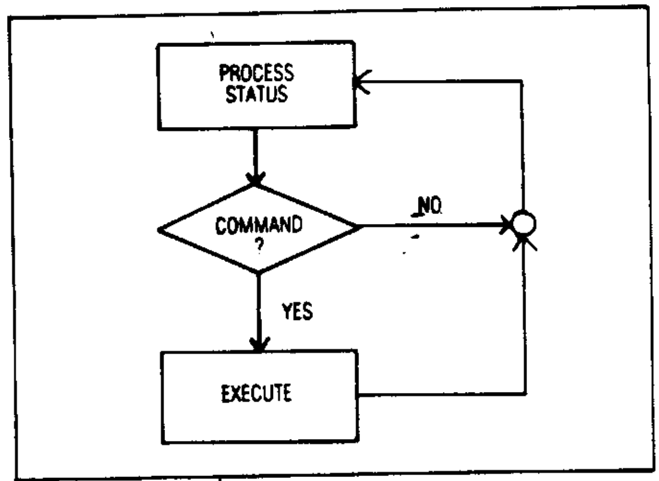

FIGURE 7. MAIN PROGRAM LOOP

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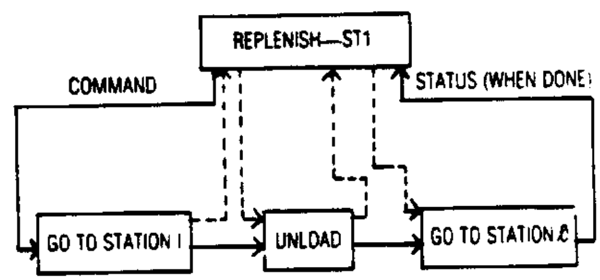

FIGURE 8. EXAMPLE OF MACRO-COMMAND

REPLENISH—ST1 is a macro-command from MHWC to Cart. Dotted lines show optional acknowledgement of commands just completed and the calling of the next command.

Software Control Algorithms and Implementation

The Cart on-board computer provides the hierarchical interface between the Cart and the MHWC. Its duties include accepting commands from the MHWC, executing associated Cart control routines, monitoring various status indicators and providing feedback information concerning the status of the Cart to the MHWC. To carry out these duties in a clear ordered fashion, the modular hierarchical approach was taken in designing and writing the software programs.

The Cart software consists of a main program which is divided into three levels of hierarchical control. At the highest level is the interface to the MHWC. The next level is an intermediate command language used to manage Cart resources. The primitive commands at the lowest level are machine dependent routines that interface directly to the Cart electronics and sensors.

The MHWC interface consists of a defined set of commands and status feedback information. A control loop (see *Figure 7*) processes status, decodes commands and executes valid commands. The control loop provides a shell isolating the internal operations of the Cart software. This shell is a precise means of controlling I/O between the end user, whether it be the MHWC or a manual operator and the Cart. If the Cart is being commanded by the MHWC, the communication is in packed binary format. If an operator is controlling the Cart, an ASCII format is used. Besides the format control features of the shell, it also has the additional benefit of circumventing any peculiarities associated with the computer operating system and the programming language with regard to error handling of I/O. As an example, if an incorrect command is entered into the on-board computer, the error is returned not as a computer run time error but as an Unrecognized Command error in the Cart Status information.

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mand aborted/not aborted) and a System Failure (volatile memory check). The third and fourth parts are the Present Magnet Location, which is null if the Cart is not reading any magnets, and the Previous Magnet Location, which gives a location with reference to the last magnet passed.

The MHWC requires the status condition of the Cart at all times. The Cart onboard computer is updating status internally at all times, but only transmits it when there is a change in status or after a fixed number of updates. Status is output using a formatted protocol, which includes header information such as message qualified (indicating type of message, i.e., status, ASCII string, etc.), a count field and a check sum, along with the information fields.

To provide a flexible and adaptable command language to the end user, an intermediate level command structure exists. As previously mentioned, the high level commands can be mnemonic commands tailored to specific tasks. Ideally, the command should be at the highest level possible such that completion of individual lower commands need not be acknowledged before attempting the next step. The intermediate commands are modular in design and are the building blocks of macro-commands. Once the function of a macro-command has been determined, it is edited into the program, compiled into a command table and is available at run time.

A typical high level command requests that, at a certain floor magnet code, a specified function be executed. These functions and more are at the lowest level of the hierarchy. Primitive commands such as start, stop, slowdown (to search and align with a tray station) and change tracks replace the matrix/switch functions that existed in the original Cart. In addition to the original Cart functions, there is a routine to monitor the reed switches and acknowledge arrival at a specified magnet location. To deliver a tray, there are routines that indicate when the cart is aligned with the tray station, that start the tray transfer mechanism, and that indicate when the transfer is completed.

Also at the lowest level of the Cart control hierarchy, the status of the cart is constantly being monitored and the associated memory buffers updated. Circuits are examined to determine the conditions of the following: travel driver (whether the Cart is moving), brakes, optical blocking (infra-red detectors looking for reflections from obstacles), safety stop (due to physical contact with bumper), guide safe (loss of guide wire signal), tray on Cart, and tray at station. These primitive commands, routines and status gathering routines control and react to the Cart electronics and sensory input.

The Cart program makes use of multitasking, which is a system-dependent feature that allows routines to execute in a parallel fashion. The multi-tasking mechanism is interrupt driven, which means that a task that is waiting for a device interrupt (e.g., a serial port) can relinquish control of the CPU (Central Processing Unit of a computer) until the interrupt arrives. This frees the CPU to run other routines. Multi-tasking is very powerful, but it must be used with caution. Its main use in the Cart program is to allow commands to be executed while status is constantly being updated and transmitted. Some of the primitive routines look for the occurrence of a certain event, such as a reed switch reacting to a floor magnet, or a mechanical switch interacting with a tray during transfer. The multitasker allows the primitive routine to watch for the vent and also allows status routines to monitor and output the results of the primitive routine. Thus, if something goes wrong during the routine which results in an endless loop, the status is available immediately to indicate the problem. This would not be the case if the program was executed sequentially.

A final point should be made concerning one other key philosophy of the AMRF. Software should always be designed and written to be as generic and portable as possible. The internal hierarchy of a program should push all machine dependent code to the lowest level. As is the case with robot control systems also being developed in the AMRF, a large portion of the Cart control system should be applicable to most AGV's.

Conclusion

The Cart has been operating extremely well for 10 months. Knowledge gained from this work has been used to write specifications for AGV's to be employed in a multi-cart system for the AMRF. Various AGV manufacturers have shown interest in supplying the Carts for integration into the AMRF. We hope to work with these manufacturers, as we do with other vendors of manufacturing equipment, to develop practical approaches for controlling AGV's and integrating them into automated factories of the future. These approaches will then be available for voluntary industry efforts to establish national or international standards.

References

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The basic commands required by the MHWC to control the Cart are: 1) go to a tray station, 2) go to a magnet location, 3) load and 4) unload. These commands actually exist at the intermediate level, but are made available to the MHWC. A typical command from the MHWC requests the Cart to go to a station, and load or unload a tray. Often the MHWC does not need to single step through these individual commands but only needs to know when the tray has been delivered. The additional acknowledgement between commands increases communications overhead and slows down the operation of the Cart. Therefore, whenever possible, a macro-command is written combining the appropriate basic commands to perform a specific task. As an example, if the Cart needs to perform a certain sequence of commands, such as Go to Station 1, Unload, and Go to Station 0; and if the only response needed by the MHWC is the arrival of the Cart at Station 0, then a macro-command can be written as REPLENISH-ST1 using the intermediate commands just mentioned (see *Figure 8*). Some questions may arise in regard to the limitations in the flexibility of such commands and the reduced control the MHWC has over the Cart. In the first case, the intermediate commands are still available when needed and in the second case, status is regularly reported to the MHWC and can be decoded, for example, to avoid an endless wait condition.

To fulfill hierarchical control requirements, the Cart indicates when the command has been successfully completed. If the Cart is unable to complete the command, status information is also required so that the MHWC can determine the problem and possibly initiate recovery procedures. Additional information such as location of the Cart, at least with reference to magnet codes, is also included.

Status can be of any length, but at present it consists of four parts. The first part is the hardware state of the Cart which indicates the state of certain Cart electronic circuits and sensory devices. The second part consists of four indicators giving the software state of the Cart: Ready for New Command (last command done/not done), Unrecognized Command (last command valid/invalid), Aborted Last Command (last com-

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